

Formation time effect on J/ψ dynamical nuclear suppression

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Abstract

The proposed hadronic and string cascade model, JPCIAE, for ultra-relativistic nucleus - nucleus collisions based on the LUND model and the PYTHIA event generator especially, is used to investigate the J/ψ suppression due to the nuclear absorption of a J/ψ in minimum bias pA and BA collisions at 200 A GeV energy. With the different sets of reasonable formation time for hadron and J/ψ the results of J/ψ suppression factor from both the usual scenario and the Glauber - like simulations are comparable with all the NA38 pA and BA data, except the NA50 data of Pb + Pb collisions. However, the difference between the usual scenario and the Glauber - like simulation, hence the difference between the dynamical simulation and Glauber theory, can not be ignored. The sensitive effect of the hadron formation time on the J/ψ suppression is studied in detail. The results seem to denote that for the J/ψ suppression the meson absorption plays role in pA as well as in BA collisions.

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More than ten years ago Matsui and Satz [1] suggested that the suppression of J/ψ yield in relativistic nucleus - nucleus collisions might be a powerful signature for the QGP formation. Since then, a number of corresponding experiments have been stimulated [2 - 4] to measure the J/ψ yield via its dimuon decay.

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A significant suppression of the J/ψ yield from pA collisions to BA collisions has already been observed in these experiments. So far, except the anomalous nuclear suppression observed in Pb + Pb reactions at 158 A GeV/c [4] the normal suppression has been well explained within the Glauber theory (absorption model) [5 - 14]. However, the mechanism for the anomalous suppression in Pb + Pb collisions is still a debating issue [9 - 15].

Recently in [16 - 17] a covariant transport approach has been used to investigate both the normal and anomalous nuclear suppression of the J/ψ yield. They concluded that the data of J/ψ suppression from pA to BA collisions, including Pb + Pb at 158 A GeV/c, can be described without assuming the formation of QGP in these collisions. However, not only their conclusions need to have more response using dynamical models but also the dynamical ingredients, such as the formation time effect, the role of meson, etc., need to have more study.

In this letter we propose a hadronic and string cascade model, JPCIAE, for relativistic nucleus - nucleus collisions based on the LUND model and the PYTHIA event generator [18]. We first inspect this model and the corresponding event generator via comparing with the NA35 data of the negative charge multiplicity, the rapidity and transverse momentum distributions of the negative charge particles and the participant protons in pp, pA, and BA collisions [19 - 20]. The model and the corresponding event generator are then used to investigate the J/ψ nuclear suppression and the effects of dynamical ingredients. The results seem to declare that all the NA38 data of J/ψ normal suppression from pA to BA collisions [2 - 3] can be fairly described by this model, except the NA50 data of Pb + Pb collisions [4]. It is also shown that the formation time of produced

particles has very sensitive effect on the J/ψ suppression and it turns out that the meson absorption plays a similar role in pA and BA collisions. We point out also the difference between two scenarios – the complete rescattering of produced hadrons (named as usual scenario) and the rescattering only between a J/ψ and other produced hadrons (named as Glauber-like).

In JPCIAE the simulation is performed in the laboratory system. The origin of coordinate space is positioned at the center of the target nucleus and the beam direction is taken as the z axis. As for the origin of time it is set at the moment when the distance between the projectile and target nucleus along z direction is equal to zero (collision time can be negative).

The colliding nucleus is depicted as a sphere with radius $\sim 1.05 A^{1/3}$ (A refers to the mass number of a nucleus) in its rest frame. The spatial distribution of nucleons in this frame is sampled randomly due to the Woods - Saxon distribution. The projectile nucleons are assumed to have an incident momentum per nucleon and the target nucleons are at rest. That means the Fermi motion in a nucleus and the mean field of a nuclear system are here neglected due to interest of relativistic energy in question. For the distribution of the projectile nucleons the Lorentz contraction is taken into account.

Then the collision time is calculated according to the requirement that the minimum approaching distance of a colliding pair should be less or equal to the value $\sqrt{\sigma_{tot}/\pi}$, where σ_{tot} is the total cross section of the colliding pair. The initial collision time list is composed of the colliding nucleon pairs, in each pair here one partner is from the projectile nucleus and the other from the target nucleus.

If the CMS energy of a colliding pair (hadron - hadron collision), selected due to the least collision time from the collision time list, is larger than or equal to ~ 4 GeV two string states are formed and PYTHIA is called to provide the produced hadrons (scattered state), no string state is formed and the conventional scattering process [21 - 23] is executed otherwise. Both of the particle list and the collision time list are then updated and they are now not only composed of the projectile and target nucleons but also the produced hadrons. The history of an event ends when the collision time list is empty.

In PYTHIA a lot of parton - parton (parton refers to quark or gluon) QCD processes have been considered, including the J/ψ production,

$$g + g \rightarrow J/\psi + g(1.3 \times 10^{-5} mb). \quad (1)$$

A user is allowed to run the program with any desired subset of these processes. We have devised a switch to turn over from the preprogrammed channel to the J/ψ production channel. It is worthy pointing out that any operation with desired subset of the processes by user, including the J/ψ production channel defined here, is a kind of bias sampling, which enhances the probabilities of those desired processes. In order to overcome the corresponding bias the selection of calling PYTHIA or of executing conventional scattering for each hadron - hadron collision is decided further according to the probability which is equal to the parametrized J/ψ production cross section [24]

$$\sigma_{NN \rightarrow J/\psi + X} = d(1 - \frac{c}{\sqrt{s}})^{12} \quad (2)$$

(with $c=3.097$ GeV, $d=2.37/B_{\mu\mu}$ nb, $B_{\mu\mu} = 0.0597$ is the branching ratio of the J/ψ to dimuons) multiplied by a factor. That factor is adjusted so that the number of J/ψ produced in each simulating event is around one, the same as in

the experiment [2].

One more point needed to be mentioned here is that in the original JETSET program, which deals with the fragmentation of a string and runs together with PYTHIA, the leading particle in a nucleon - nucleon collision is assumed to carry about half of the incident energy. But the experiments of nucleus - nucleus collisions at relativistic energies reveal that a incoming nucleon loses a smaller fraction of its energy in each binary nucleon - nucleon collision except its last collision with the target nucleon, in which it loses about half of its energy, and a stopping law is proposed in [25 - 26] to handle this situation. We in this program have also applied the stopping law to calculate the energy fraction that a leading particle takes after each binary nucleon - nucleon collision.

For inspecting the model and the corresponding program (event generator) we first compare the calculated (using preprogrammed channel) negative charge multiplicity, the rapidity and transverse momentum distributions for the negative charge particles and for the participant protons in pp, pA, and BA collisions with the corresponding data [19 - 20]. The comparisons of negative charge multiplicity for pp and pA reactions are shown in Tab. 1 and for BA in Tab.2 . Fig. 1 gives the comparison for the rapidity distributions of the negative charge particles in central S + S and N + N minimum bias collisions (upper frame) and for the participant protons in S + S central and peripheral collisions (lower frame). The transverse momentum distributions in central S + S collisions for the negative charge particles and for the participant protons are given in the upper frame and the lower frame of Fig. 2, respectively. One sees from these tables and figures that the agreement between theory and experiment is

reasonably good.

We are then turning to the calculations with J/ψ production channel. Since the purpose of this letter is to explore the physics behind the NA38 and NA50 data and not to fit the data as good as possible. We first fix two reasonable sets of parameters to calculate the J/ψ suppression factors in minimum bias pA and BA collisions at the scaled energy 200 A GeV and compare them with the corresponding data in Fig. 3. The experimental J/ψ suppression factor is defined as [17]

$$S_{exp.}^{J/\psi} = \left(\frac{B_{\mu\mu}\sigma_{BA}^{J/\psi}}{\sigma_{DY,2.9-4.5GeV}} \right) / \left(\frac{B_{\mu\mu}\sigma_{pd}^{J/\psi}}{\sigma_{pd}^{DY}} \right), \quad (3)$$

since the J/ψ yield is measured via its dimuon decay and the Drell - Yan provides the background of the dimuon invariant mass spectrum. As for the theoretical definition of the J/ψ suppression factor it is expressed as [17, 27]

$$S_{theo.}^{J/\psi} = \frac{M_{J/\psi}}{M_{J/\psi}(0)} \quad (4)$$

where $M_{J/\psi}(0)$ refers to the multiplicity of primary J/ψ and $M_{J/\psi}$ to the multiplicity of J/ψ after final interactions. The open circles with error bar in Fig. 3 are the experimental data (cited directly from [27]). In Fig. 3 the full circles are the results of usual scenario calculations with parameter set 1: the meson formation time $\tau_M = 1.2$ fm/c and the J/ψ formation time $\tau_{J/\psi} = f_{J/\psi} \times \tau_M$, $f_{J/\psi} = 0.5$, the full triangles are the results of Glauber - like calculations with parameter set 2: $\tau_M = 0.8$ fm/c, and $f_{J/\psi} = 0.5$, and the open triangles are the results of Glauber - like calculations with parameter set 1. As for the nucleon formation time it is assumed to be zero. Since the cross section of J/ψ - hadron interaction is still an open problem [28 - 29], we do not address this question here and adopt simply the values: $\sigma_{J/\psi-B}^{Abs} = 6$ mb and $\sigma_{J/\psi-M}^{Abs} = 3$ mb as

usual. The corresponding total cross section used in the program are $\sigma_{J/\psi-B}^{tot} = 7.2$ mb and $\sigma_{J/\psi-M}^{tot} = 4.0$ mb. The following reactions of J/ψ with B (baryon) and M (meson) are considered

$$J/\psi + B \rightarrow \Lambda_c + \bar{D}, \quad (5)$$

$$J/\psi + M \rightarrow D + \bar{D}. \quad (6)$$

One sees from Fig. 3 that both the results of the usual scenario with parameter set 1 and the results of Glauber - like calculations with parameter set 2, i.e. the full circles and the full triangles, are comparable with all the experimental data, except the NA50 data of Pb + Pb reactions. However, the Glauber - like calculation needs to have a smaller meson formation time than the usual scenario, as the freeze - out time of a hadron in the usual scenario is longer than ones in the Glauber - like situation. That is because the reinteraction between hadrons (except J/ψ) is not taken into account in the Glauber - like situation. Comparing the results of usual scenario with the results of Glauber - like calculation using the same parameter set 1 (cf. the full circles and the open triangles in Fig. 3) one knows that the difference between the usual scenario and Glauber - like situation and then between the dynamical simulation and the Glauber theory should not be ignored. This conclusion is in consistent with [16 - 17]. Of course, the difference between the usual scenario and Glauber - like situation is also formation time dependent.

Tab. 3 gives the J/ψ suppression factor calculated for minimum bias p + Al, p + Cu, p + Ag, P + U, O + Cu, and O + U collisions at 200 A GeV under the usual scenario and the parameters of $f_{J/\psi} = 0.5$ and of various τ_M . Tab. 4 gives the results calculated for the same collisions as the ones in Tab. 3 but

with parameters of $\tau_M = 1.2$ fm/c and of various $f_{J/\psi}$. These tables indicate that the J/ψ suppression factor is very sensitive to the formation time of meson and J/ψ . At the same formation time of meson and J/ψ the J/ψ suppression factor, both in pA and BA collisions, decreases with the increasing of target mass. In the case of $1 + A^{1/3}$ (pA collision) $\simeq B^{1/3} + A^{1/3}$ (BA collision, B and A here refer also to the mass numbers of projectile and target nuclei) the J/ψ suppression factor in pA collision is larger than ones in BA collision, that is because of the less hadrons are produced in pA than in BA collisions.

In order to check whether mesons play different role for the J/ψ suppression in pA and BA collisions at the same incident energy and centrality, a factor defined by

$$f_M = \frac{S_{theo.}^{withoutM} - S_{theo.}^{withM}}{S_{theo.}^{withoutM}} \quad (7)$$

is introduced. The results of f_M calculated for the same collisions as the ones in Tab. 3 under the usual scenario and the parameter set 1, are given in Tab. 5. One sees from this table that in pA collisions the role of mesons in the J/ψ suppression is not negligible and it is increased with the increasing of target mass. That is inconsistent with the conclusion in [6 - 13, 16 - 17]. At the fixed mass of the projectile nucleus the effect of meson on the J/ψ suppression depends mainly on the mass of the target nucleus both in pA and BA collisions.

In summary We have proposed a hadronic and string cascade model, JPCIAE, for ultrarelativistic nucleus - nucleus collisions based on the LUND model and the PYTHIA event generator especially. It has been used to investigate the J/ψ suppression in minimum bias pA and BA collisions at the scaled energy of 200 A GeV. With the different sets of reasonable formation time for hadron and

J/ψ the results of J/ψ suppression factor from both the usual scenario and the Glauber - like simulations are comparable with all the NA38 pA and BA data, except the NA50 data of Pb + Pb collisions. However, the difference between the usual scenario and the Glauber - like simulations, hence the difference between the dynamical simulation and Glauber theory, can not be ignored. The sensitive effect of the hadron formation time is studied in detail. Meanwhile, the results seem to denote that for the J/ψ suppression mesons play role in pA as well as in BA collisions.

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Figure Captions

Fig. 1 The rapidity distributions for (a) h^- and (b) participant proton. The N+N data and corresponding results of JPCIAE have been multiplied by 10 for the convenience of comparison. The labels are the experimental data and the curves are the corresponding results of JPCIAE.

Fig. 2 The transverse momentum distributions for (a) h^- and (b) participant proton. The labels are the experimental data and the the curves are the corresponding results of JPCIAE.

Fig. 3 The J/ψ suppression factor versus the product of mass numbers of the projectile and the target nuclei in minimum bias pA and BA collisions at 200 A GeV. See text for the detail.

Table 1. Negative charge multiplicity in pp and mini bias pA collisions at 200 GeV/c

	p + p	p + S	p + Ag
NA35 data	2.85±0.3	5.7±0.2	6.2±0.2
JPCIAE	2.84	4.91	5.81

Table 2. Negative charge multiplicity in central BA collisions at 200A GeV

	S + S	S + Ag
NA35 data	98±3	170±8
JPCIAE	107	173

Table 3. J/ψ suppression factor in the reactions of p+Al, p+Cu, p+Ag, p+U, O+Cu, and O+U at 200A GeV, $f_{J/\psi}=0.5$

$\tau_M(fm/c)$	p + Al	p + Cu	p + Ag	p + U	O + Cu	O + U
0.2	0.220	0.194	0.180	0.122	0.144	0.103
0.5	0.435	0.403	0.369	0.314	0.313	0.246
1.2	0.888	0.836	0.779	0.738	0.713	0.635

Table 4. J/ψ suppression factor in the reactions of p+Al, p+Cu, p+Ag, p+U, O+Cu, and O+U at 200A GeV, $\tau_M=1.2$ fm/c

$f_{J/\psi}$	p + Al	p + Cu	p + Ag	p + U	O + Cu	O + U
0.25	0.538	0.496	0.472	0.453	0.389	0.343
0.50	0.888	0.836	0.799	0.738	0.713	0.635
0.75	0.943	0.932	0.921	0.859	0.832	0.773

Table 5. The factor f_M in the reactions of p+Al, p+Cu, p+Ag, p+U, O+Cu, and O+U at 200A GeV, $\tau_M=1.2$ fm/c and $f_{J/\psi}=0.5$ fm/c

reaction	p + Al	p + Cu	p + Ag	p + U	O + Cu	O + U
$S_{theo.}^{withoutM}$	0.903	0.865	0.875	0.810	0.772	0.706
$S_{theo.}^{withM}$	0.888	0.836	0.799	0.738	0.713	0.635
f_M	0.0166	0.0335	0.0869	0.0889	0.0764	0.101

FIG. 1

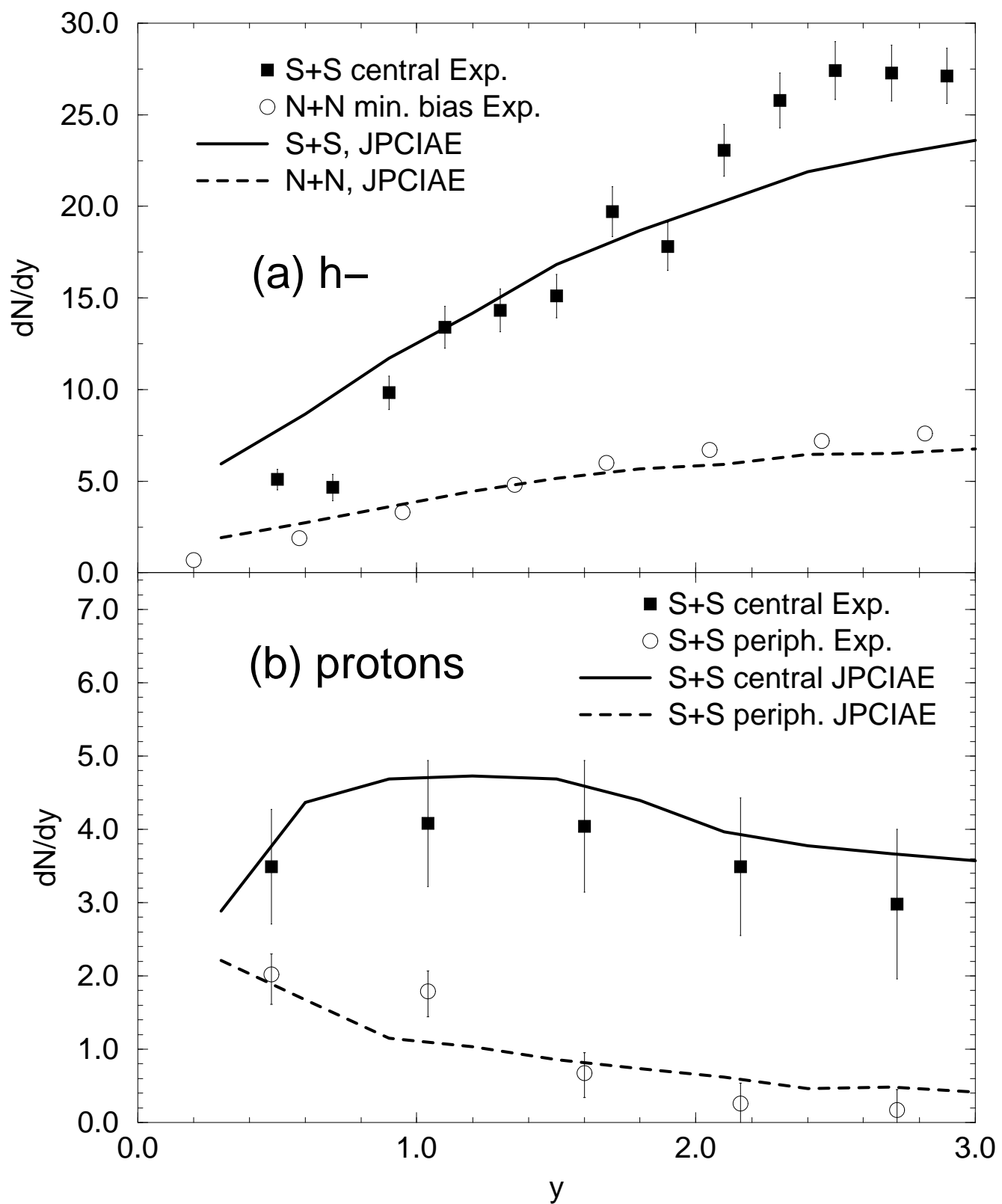
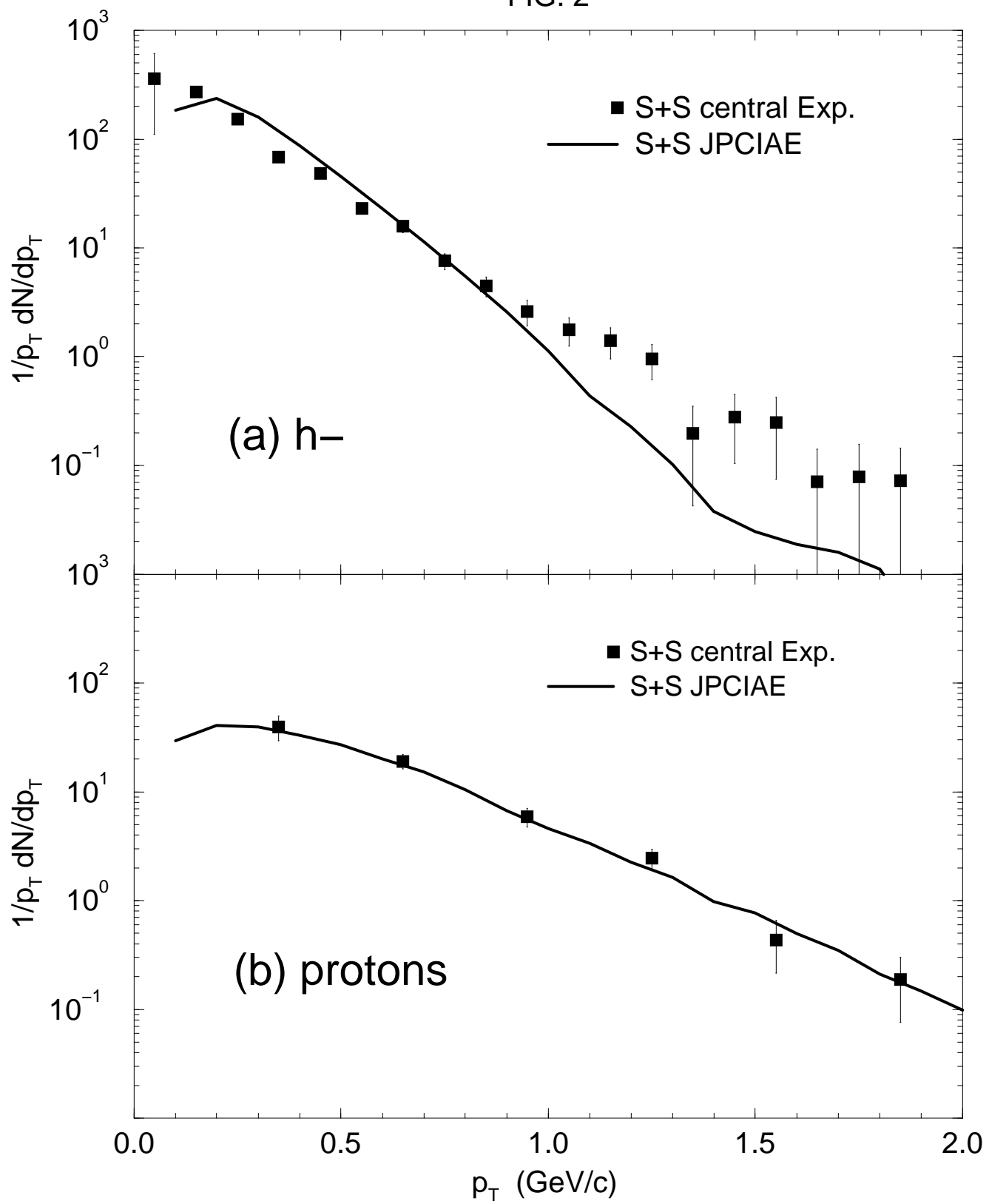


FIG. 2



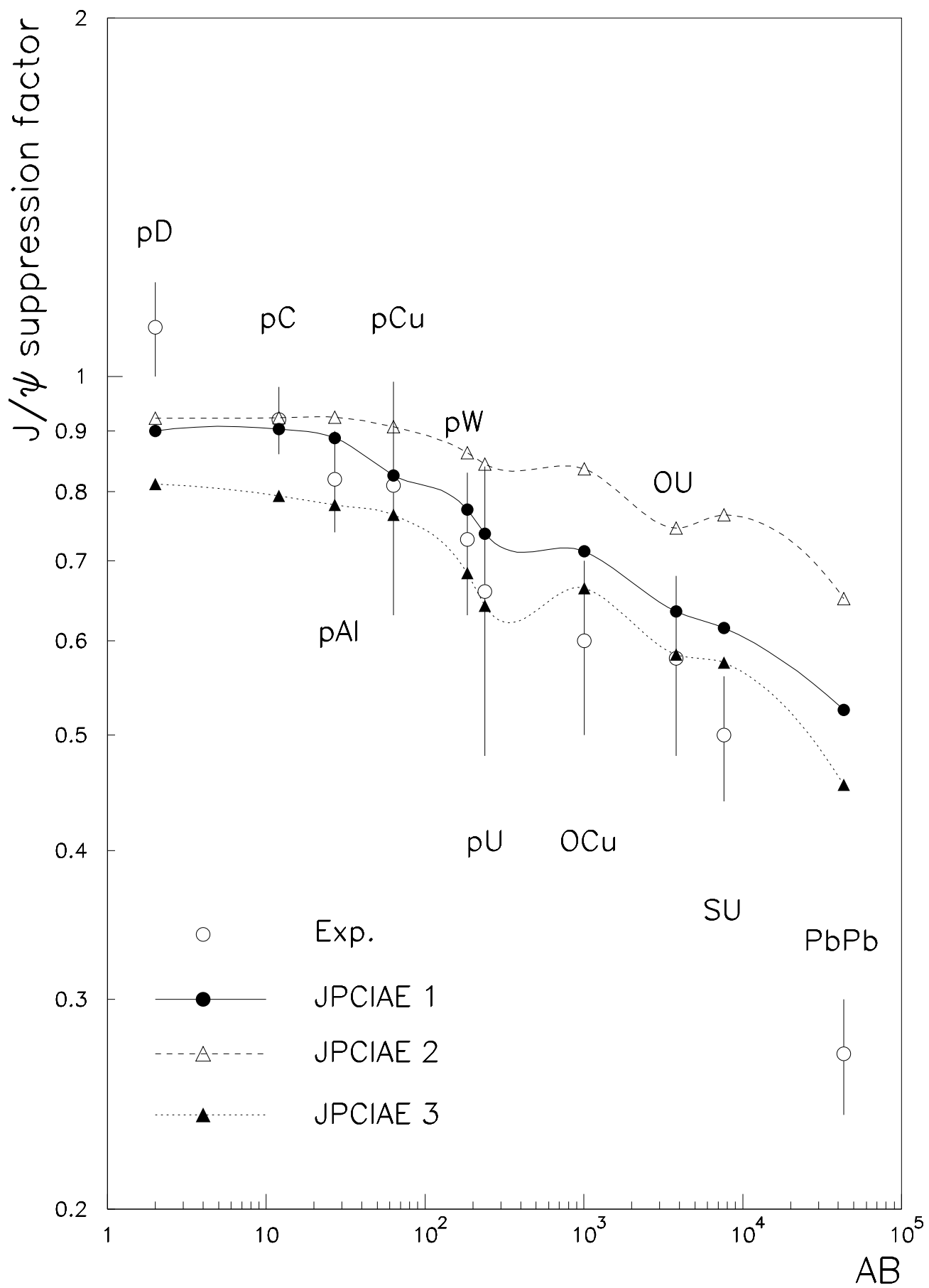


FIG. 3